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The research program has made substantial advances in areas relevant to the use of low energy electron beams and microfabricated electron beam columns for high resolution lithography. The first was the development of novel cold field emission sources. Focused ion beam milling was used to demonstrate the effectiveness of self-shielding to enhance electron emission on a variety of cold field electron sources as well as fabrication of apertures in silicon membranes. Titanium nitride thin films have been characterized for use as coatings on tungsten field emitters. These films provide robust, inert, stable emission surfaces capable of milliampere emission currents without requiring high temperature processing. The films can be coated on a variety of base emitter structures. The second area of research at Cornell focused on low energy electron beam lithography processes compatible with high throughput microcolumn electron beam lithography. Two new resist systems were evaluated, and systems demonstrated the target sensitivity of 1 microcoulomb per square centimeter needed to achieve high throughput. The final area involved the development of pattern transfer processes for silicon device fabrication. Both resist systems were used as an etch mask to etch bulk silicon using low energy chlorine ions from an electron cyclotron plasma etch system.

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Executive summary:

Microfabricated electron beam columns are new devices that could be used for high-throughput high-resolution electron beam lithography for advanced electronic device fabrication. The utility of such devices depends on the ability to fabricate high quality components for the electron columns and the ability to use the relatively low energy electron beams for fabrication processes. In this research program activity was directed at evaluating new types of microfabricated electron emitters and studying low energy electron beam resists and processes. The research was done in collaboration with the research group at IBM Watson Research Center .

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Research results:

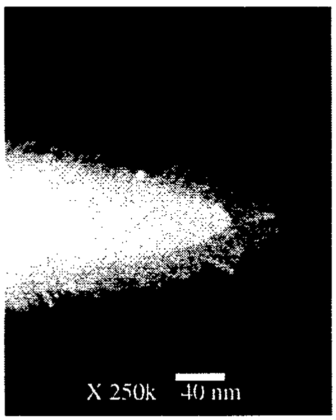
The two primary areas of research involved the study of electron sources and low energy electron beam processes. The electron source work centered on the design fabrication and testing of cold field emitters specifically for use in lithography. The requirements on electron sources for lithography are different for those for displays of other applications.

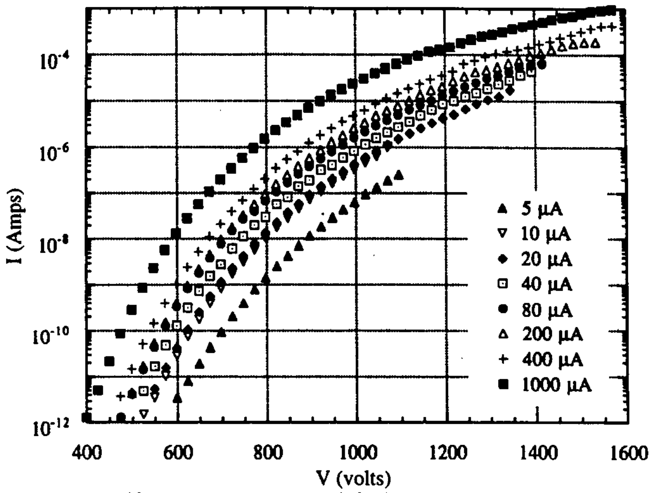
The research results have been published in available journals. In the following sections we present abstracts and summaries of the research. The interested reader is referred to the publications for the full details.

Microfabricated electron field emitters:

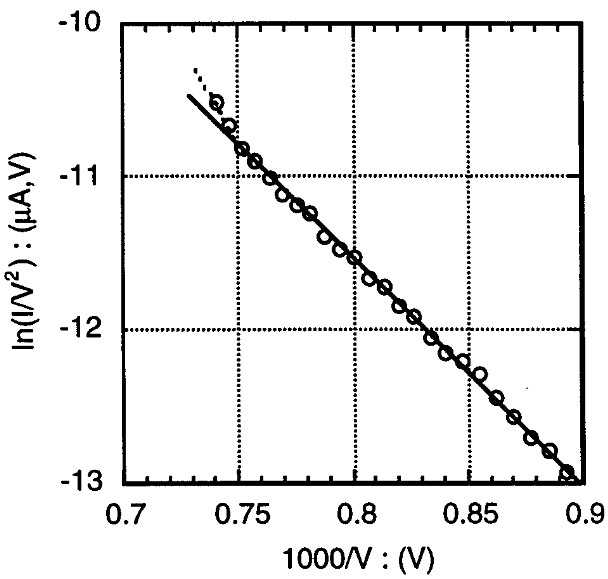
In the study of electron field emitters the issues of source brightness, stability, and energy spread are important parameters for lithographic use. The ability to fabricate unheated (cold) field emitter tips is desirable for use in arrayed column systems. To this end various approaches in terms of tip materials, geometry and fabrication methods were studies. Figure 1 shows the type of results obtained for experimental electron emitter systems. Details on specific systems appear in the references.

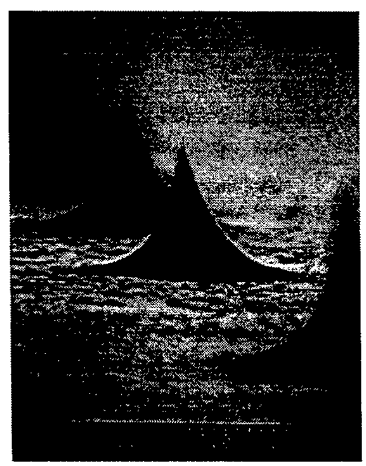
Fig. 1 Examples of structural and electrical measurements oncold field emission sources





I-V curves of the voltage cycling process which activates TiN coated W field emitters with no thermal processing.





Fowler Nordheim data for glassy Carbon field emission arrays prepared on planar substrates with O_2 RIE.

Electron field emission properties of self-shielded tungsten sources [1]

The electron emission properties of self-shield single crystal tungsten (W) tips were studied by field emission microscopy and spectroscopy. Self-shielded tips were formed by focused ion beam milling an annular depression on the apex of an electrochemically etched W <111> tip. The resultant tip structure consists of a flat bottomed crater (the outer rim of which forms the shielding electrode) with a central protrusion (the emitter). In situ processing consisted of moderate thermal flashing and partial buildup. Significantly greater angular emission current densities were measured, as compared to both unshielded W<111> built-up tips and standard W<310> tips. Energy analysis of the emitted electrons showed no deviations from normal W<111> emission. Self-shielding may offer a generally applicable method for increasing the brightness of field emission sources in a variety of electron optical instruments.

Titanium nitride coated tungsten cold electron field emission sources [2]

Titanium nitride (TiN) thin film coatings were studied by field emission microscopy and spectroscopy. Coated tungsten tips were found to be capable of emitting extremely high currents at low extraction voltages (~1 mA at 900-1700 V). Current fluctuations for >400 μA total emission from a single tip were 7% rms, measured over ~1 h. Electron energy distributions measured <0.5 eV (full width at half-maximum). Since TiN thin films are commonly used in the microelectronics industry, TiN coatings have the potential for being a relatively simple and widely accessible method for improving the performance of cold field emission sources.

Fabrication of arrayed glassy carbon field emitters [3]

Glassy carbon has desirable properties for electron field emission such as surface inertness, electrical conductivity, and thermal stability. In addition, a uniform thick substrate with a polished surface is easily obtainable. This enables one to apply large scale integrated circuit processing for fabricating arrayed tips. By using oxygen reactive ion etching, cusps over 3.5 μm in height and 2.5 μm in base diameter are fabricated with a tip radius of under 10 nm. The process is assisted by the formation of a layer of etch products which protects the newly forming tip from bending and over etching. The field emission current up to 50 μA from the glassy carbon tips is obtained by applying high voltage to a mesh anode. The current which passed through the mesh anode is collected at another electrode and measured. The Fowler-Nordheim plot suggests the existence of nm scale structure on the tip. This favorable result indicates glassy carbon substrate is a good substrate for field emitter arrays.

Low energy electron beam processes:

The limited electron penetration depth at electron energies in the 1-2 keV range of microfabricated columns presents a challenge for fabrication processes. This range is on the order of a few tens of nm and is significantly shorter than for conventional electron beam lithography at higher energies (see figure 2). issues of electron scattering were addresses in this research as was the development of resist systems and pattern transfer for device structure fabrication.

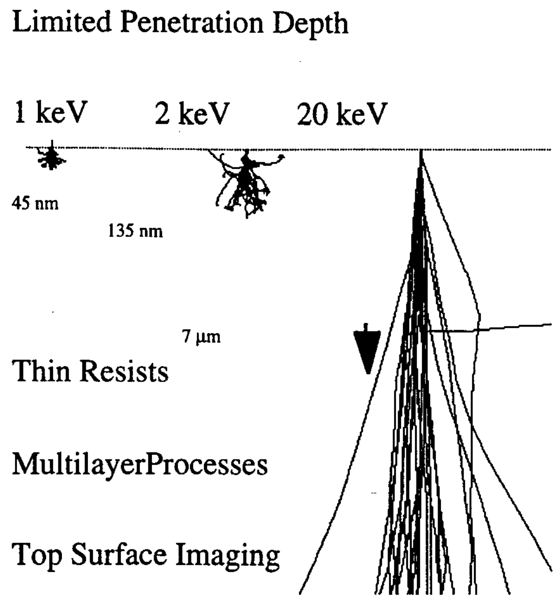


Fig. 2 Results of Monte-Carlo simulation of electron trajectories in PMMA resist at electron energies of 1,2 and 20 keV.

Resists and processes for 1 kV electron beam microcolumn lithography [4]

Low-voltage electron beam lithography has been considered for some time for high-resolution lithography because of reduced proximity effects, increased resist sensitivities, and reduced substrate damage. An accelerating voltage of 1 kV is being considered for the operation of microcolumns that are being developed for use in an innovative, high-speed, high-resolution electron beam lithography system. The development of resists and processes for use at 1 kV then becomes one of the essential components in this developing technology. Since 1 keV electrons have a penetration depth of ~60 nm in organic polymers, the resists used for electron beam exposures must be correspondingly thin. This makes the development of processes for pattern transfer a challenge. Here, we report on three resist and processing schemes for use at 1 kV which can be used to produce 50-100 nm wide structures. Structure as small as 50 nm wide with 3 to 1 aspect ratios, and trenches 300 nm deep and less than 100 nm wide have been successfully transferred into Si substrates. Despite the use of very thin resists, the transferred patterns do not suffer from noticeable defects.

Studies of 1 and 2 keV electron beam lithography using silicon containing P(SI-CMS) resist [5]

We have investigated low voltage electron beam lithography at 1 and 2 keV using P(SI-CMS) resist. With this system, 10:1 aspect ration, 80-nm-wide polyimide fins, and >7:1 aspect ratio, 80-nm-wide Si fins were fabricated using 2 kV exposures. Analysis of our results suggests that observed reductions in the process latitude at 1 kV are not resist specific and can be understood on the basis of electron scattering. Experimental comparisons have been made by exposure of PMMA. In order to describe the results and help guide future development, we have conducted Monte Carlo simulations and experimental studies of the energy deposition in resists by 1 and 2 keV beams.

High resolution electron beam lithography using ZEP-520 and KRS resists at low voltage [6]

ZEP-520 and KRS resist systems have been evaluated as candidates for use in low voltage electron beam lithography. ZEP-520 is a conventional chain scission resist which has a positive tone for over two orders of magnitude in exposure dose. KRS is a chemically amplified resist which can be easily tone reversed with a sensitivity ~8 $\mu C/cm^2$ at 1 keV. Both resist systems are shown to have sensitivities ~1 $\mu C/cm^2$ for positive tone area exposures to 1 keV electrons. A decrease in contrast in 50 nm thick resist layers is seen when exposure voltage is lowered from 2 to 1 keV, indicating nonuniform energy deposition over the resist thickness. High resolution single pass lines have been transferred into both Si and SiO_2 substrates at both low and high voltages in each resist system without using multilayer resist masks. The ZEP-520 and KRS resists are shown to have resolutions of 50 and 60 nm, respectively, at 1 kV, within a factor of 2 of their high voltage resolutions under identical development conditions. A cusp shaped etch profile in Si allows high aspect ratio 20 nm wide trenches to be fabricated using these resists on bulk Si. Low voltage exposures have been used to pattern grating with periods as small as 75 and 100 nm in ZEP-520 and KRS, respectively. Low voltage exposures on SiO_2 show no indications of pattern distortion due to charging or proximity effects.

Low energy electron beam top surface image processing using chemically amplified AXT resist [7]

High resolution processes are demonstrated with a positive-mode chemically amplified AXT top surface imaging resist system exposed with a low energy electron beam. Top surface imaging is an ideal match to low energy electron beam lithography because it allows thick resist layers to be patterned despite the limited penetration depth of the electron beam. The three key steps of the process are exposure, silylation, and etch development. All three steps influence the final process sensitivity, contrast, and resolution. The AXT has a poly (hydroxy styrene) base resin, and has been formulated both with and without a dye used to enhance optical absorption. We have achieved sub 100 nm resolution both with and without a post exposure bake. Critical area doses below 1 $\mu C/cm^2$ are demonstrated. The edge roughness and density of etch residue from silylation defects have been compared for a variety of oxygen plasma etch systems.

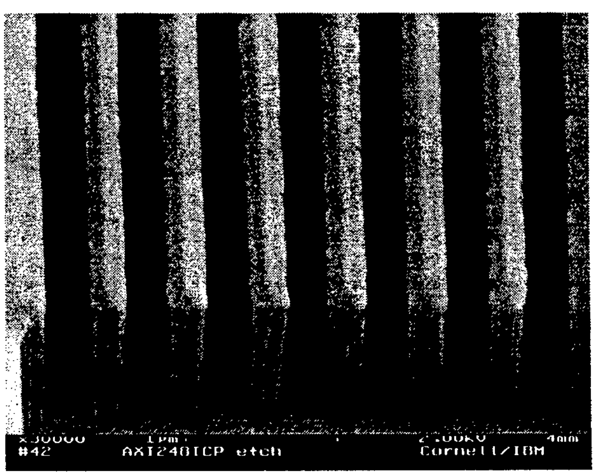


Fig. 3. Patterns in AXT-248 top suface imaging resist after low energy electron beam exposure and plasma etch development in a transformer coupled plasma RIE.

Personnel:

The principal investigators on this project were Professors Harold G. Craighead and Michael S. Isaacson of the School of Applied and Engineering Physics, Cornell University. Postdoctoral researchers. C. W. Lo, William Lo, David Tanenbaum, M. Rooks, Pamela St. John and Robert Davis worked on this effort. as did Ph.D. student C. Gemmill. All of these students and postdoctoral researchers are now employed by US Industry except for R. Davis who is at this time still a postdoctoral researcher at Cornell and David Tanenbaum who is now professor at Pomona College in California.

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